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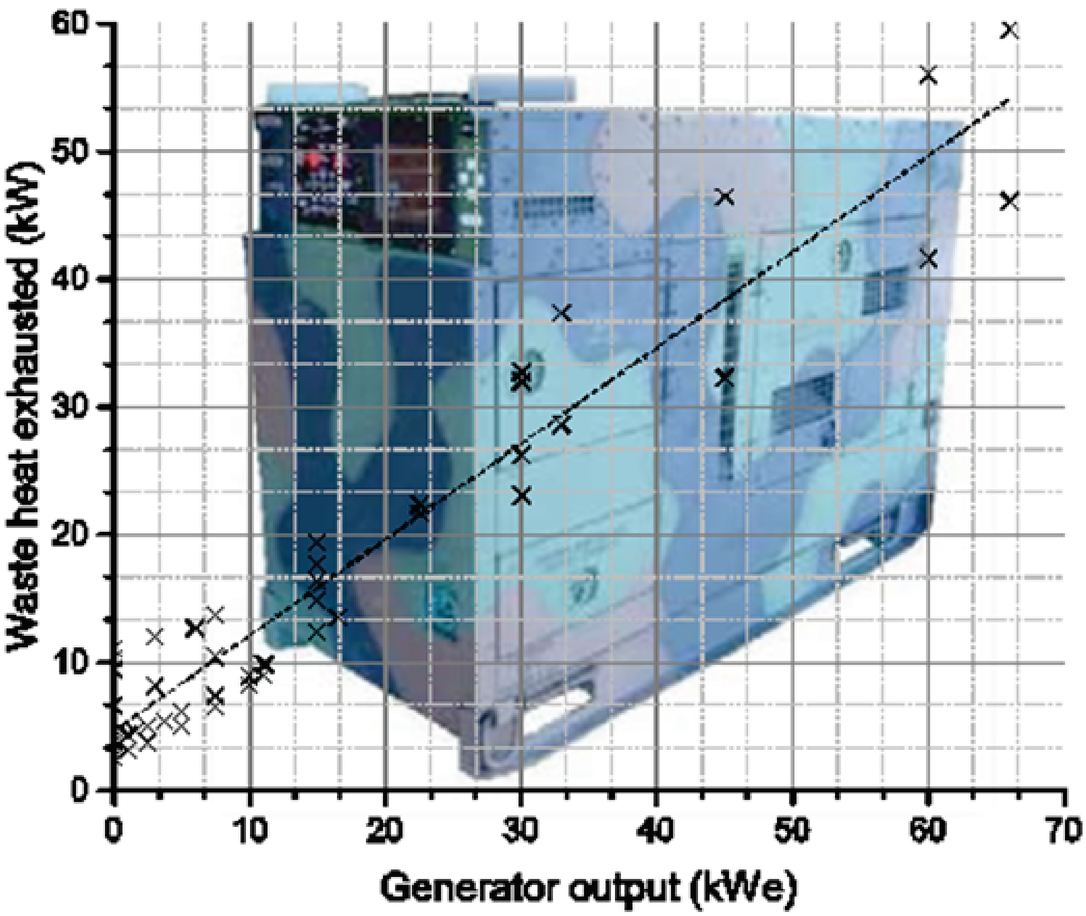

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Abstract

The energy requirements of contingency bases (CBs) involved in U.S. military operations on every continent are met almost exclusively with the use of diesel generators, which are relatively inefficient both in terms of fuel consumption and the large amounts of waste energy generated during their operation. Tactical generators are currently loaded only to 30 to 40% capacity, due in large part to the sizing of generators to cover large electrical loads like electric heating of space and water. This work was undertaken to estimate the amount of available waste heat that could be captured and reused to heat (or cool) buildings and provide hot water while reducing generator fuel demand. It was found that the use of otherwise wasted thermal by-product of the diesel generator for space and water heating allows loads to be consolidated so the numbers and sizes of generators can be dramatically reduced. The use of cogeneration can lead to total fuel savings of nearly 20%. Waste heat from five 60 kW generators can supply water heating for an entire 300 PAX contingency base, and in austere conditions, one 30 kW generator can provide up to 1.75 gpm of instantaneous hot water.

Executive Summary

The *U.S. Army Concept Capability Plan (CCP) for Army Base Camps in Full Spectrum Operations for the Future Modular Force 2015 – 2024* calls for increased flexibility in base camp operations through sustainable and adaptable designs. Yet the energy requirements of contingency bases (CBs) involved in U.S. military operations on every continent are met almost exclusively with the use of diesel generators, from small 10-kW organic tactical generators to multiple megawatt leased generators, which primarily use fuels such as JP-8. Moreover, the generators that burn this fuel are relatively inefficient, both in terms of fuel consumption and the large amounts of waste energy generated during their operation.

Research and development in areas such as waste heat recovery are critical because today's CBs are not currently operated for optimal energy efficiency. As yet, there is no program of record system in place to capture and reuse the heat created by the generators. Capturing otherwise wasted thermal energy and using it to meet requirements such as buildings heat and hot water for hygiene would reduce the total amount of JP-8/diesel required. In a broader context, the ability to recover the currently wasted thermal energy will also reduce the manpower and security requirements associated with the logistics of fuel supply. Fuel convoys consist of not only the fuel tankers and their drivers, but also the Soldiers in the associated security elements. Since the risk of attack remains high for fuel convoy operations, reducing the number of fuel convoys needed saves not only resources, but potentially Soldiers' lives.

Currently, Forward Operating Bases (FOBs) use Environmental Control Units (ECUs) to regulate temperature; however ECUs require a significant portion of the energy produced by the generator to achieve this. Simultaneously, the generator itself produces a large amount of thermal energy during the combustion process that is simply lost to the environment. If this thermal energy could be captured for heating of spaces or water (or cooling spaces, via absorption chillers), high energy devices such as ECU's and water heater use could be reduced or even eliminated. This work investigated the feasibility of using waste heat from generators to reduce energy required by Environmental Control Units (ECUs) in B-Huts and Air-Beams in a variety of potential climates.

Simulation results for B-huts and AirBeam tents, in all climates, show that cogeneration from tactical generator waste heat recovery functions well for both 30 and 60-kW generators. For both sizes operated at 50% of rated load, in all locations considered, 100% of the AirBeam demand can be supplied, and at least 96% of B-Hut demand can be supplied. In several scenarios, multiple shelters' demands can be supplied at rates greater than 90%. All calculated scenarios show a net positive energy savings, with a range of 17-48% fuel savings per implementation. A 300 PAX camp developed for baseline purpose showed a total fuel savings of nearly 20%. Implementation of cogeneration can lead to total fuel savings of 19.8% over baseline configuration in a 300 PAX base camp and fuel savings of up to 18.5% in a 50 PAX base camp. For the 300 PAX base camp, this reduces the need for fuel convoys from one every 4 days to one every 5 days.

The feasibility of using recovered waste heat from generators for shelter environmental control was accomplished through a two part process. First, typical FOB buildings (B-Huts and AirBeams) were modeled in four possible climates (temperate, desert, rain forest, and arctic) using EnergyPlus™, to determine the hourly heating and cooling demands over the course of 1 year. In parallel, waste energy was calculated using exhaust data from several different tactical generators of a range of capacities. This model estimated the amount of thermal energy that was extractable hourly from the generator exhaust using Commercial off-the-shelf (COTS) heat exchangers, liquid storage tanks, and pumps to then heat (or cool, using COTS sorption chillers) B-Huts and AirBeams. Finally, the demand was compared to the available energy supply.

Waste heat recovery (WHR) can also be used to supply heated water to both reduce energy demand and increase quality of life (with no additional burden). For a 300 PAX base camp, the total supply of heated water could be provided from the waste heat of five 60-kW generators operating at 50% load. In a 50 PAX base camp, average daily water usage is limited, and does not always include heated water. It would be possible to incorporate a simple water heating system to supply small amounts of heated water for personal hygiene use. Simulations predict that a 30-kW generator operating at 50% load is enough to supply 1.75 gpm of instantaneous hot water at 40 °C (104 °F) from a 50 °F (10 °C) supply of cold water, i.e., enough hot water to supply one continuous shower per generator.

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Preface

This study was conducted for Army Studies Program (ASP) under Military Interdepartmental Purchase Request (MIPR) 0010617298 “Waste Heat Recovery Opportunities for Contingency Bases.” The technical monitors were Rob Lambert, ASP Project Coordinator, and Megan Mariman, ASP Director.

The work was performed by the Energy Branch (CF-E) of the Facilities Division (CF), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). The Principal Investigator was Charles T. Decker, CEERD-CFE. At the time of publication, Andrew Nelson was Chief, CEERD-CFE; L. Donald K. Hicks was Chief, CEERD-CF; and Kurt Kinnevan, CEERD-CZT was the Technical Director for Installations. The Deputy Director of ERDC-CERL was Dr. Kirankumar V. Topudurti and the Director was Dr. Ilker R. Adiguzel.

COL Bryan S. Green was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

1 Introduction

1.1 Background

The *U.S. Army Concept Capability Plan (CCP) for Army Base Camps in Full Spectrum Operations for the Future Modular Force 2015 – 2024* calls for increased flexibility in base camp operations through sustainable and adaptable designs. Yet the energy requirements of contingency bases (CBs) involved in U.S. military operations on every continent are met almost exclusively with the use of diesel generators, from small 10-kW organic tactical generators to multiple megawatt leased generators, which primarily use fuels such as JP-8 (Figure 1). For Fiscal Year 2015 (FY15) the Army is predicted to consume 21.7 million barrels of liquid fuel at a staggering cost of $3.4 billion (DoD 2014). Moreover, the generators that burn this fuel are relatively inefficient, both in terms of fuel consumption and the large amounts of waste energy generated during their operation.

Research and development in areas such as waste heat recovery (WHR) are critical because today's CBs are not currently operated for optimal energy efficiency. There is no program of record system in place to capture and reuse the heat created by the generators. Capturing otherwise wasted thermal energy and using it to meet requirements such as buildings heat and hot water for hygiene would reduce the total amount of JP-8/diesel required. For example, a typical Tactical Operations Center (TOC) can require approximately 15 kW to operate. If the heat recovery system removes the need for a 5-kW load for external heaters, the generator used for the TOC could be sized down from a 15 to a 10-kW generator. Achieving such higher efficiency from existing power generation and utility systems would in turn reduce the base's overall fuel supply requirement.

Figure 1. Examples of tactical generator sets.

In a broader context, the ability to recover the currently wasted thermal energy will reduce the manpower and security requirements associated with the logistics of fuel supply. Such constructive changes cascade up the supply chain. A facility that switches to a smaller generator requires less fuel, which helps to minimize the number of fuel trucks and ultimately the number of fuel convoys needed to supply the base. Fuel convoys consist of not only the fuel tankers and their drivers, but also the Soldiers in the associated security elements. Since the risk of attack remains high for fuel convoy operations, reducing the number of fuel convoys needed saves not only resources, but potentially Soldiers' lives.

These "cogeneration" systems (which produce both electricity and heat for immediate use) recover waste heat from the generator exhaust to improve overall efficiency and significantly reduce fuel demands. Cogeneration processes, such as combined heat and power (CHP) and combined cooling, heat, and power (CCHP) have been in practice in large scale systems for several decades, but recent advances in small scale "micro-cogeneration" have opened the door for application of these technologies in CB scale energy generation. To successfully implement cogeneration, the system design must be simple to construct; it must use readily accessible components; and it must not adversely affect generator operation.

This work was undertaken to help fill that need through simulations that estimate the amount usable of available waste heat and the amount of heat required per building in a range of climates. These results will provide information to determine the combinations of generators, locations, and structures that are feasible to implement WHR. This analysis includes a technically-rigorous evaluation of opportunities for WHR at CBs, with a primary focus on the capture and reuse of waste heat from tactical electricity generators using simple heat exchange systems, also known as cogeneration. In parallel, thermal heat demands and potential applications of recovered heat are assessed in terms of payback, practicality, safety, manpower impacts, and Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) implications. The assessment of potential uses of waste heat includes:

- water for radiant heating of structures
- cooling via absorption chillers
- hot water for showers and shaving
- Rankine cycle electric generators
- hot water for Dining Facilities (DFACs)

- hot water for laundry
- heat for atmospheric water generators.

1.2 Objectives

The objective of this work was to simulate and analyze the feasibility and potential payoff of the use of heat recovery systems at CBs as a function of base size and climate.

1.3 Approach

The objectives of this work were met through the following steps:

1. A literature review was conducted into two combined topics: WHR, and existing military equipment used for contingency basing. Primary sources included the Defense Technical Information Center (DTIC), ASPdb, the ERDC online technical library, professional technical journals, and manufacturers' technical specifications.
2. Simulations were performed for B-huts and AirBeam tents, in all climates, to test how well cogeneration from tactical generator WHR would function for 10, 15, 30, and 60 kW generators.
3. The feasibility of using recovered waste heat from generators for shelter environmental control was tested through a two part process:
    a. Typical FOB buildings (B-Huts and AirBeams) were modeled in four possible climates (temperate, desert, rain forest, and arctic) using EnergyPlus™, to determine the hourly heating and cooling demands over the course of 1 year.
    b. Waste energy was calculated using exhaust data from several different tactical generators of a range of capacities. This model estimated the amount of thermal energy that was extractable hourly from the generator exhaust using Commercial off-the-Shelf (COTS) heat exchangers, liquid storage tanks, and pumps to then heat (or cool, using COTS absorption chillers) B-Huts and AirBeams.
    c. Finally, the demand was compared to the available energy supply.
4. Calculations were done to test whether WHR can be used to supply heated water to both reduce energy demand and increase quality of life (with no additional burden).
5. Conclusions were drawn and recommendations made for further work.

2 Literature Review

One of the three strategic principles of the U.S. Department of Defense's (DoD's) Operational Energy Strategy is "more fight, less fuel" (DoD 2011). A review of literature in DTIC and the Army Study Program Database (ASPdb) reveals that heat recovery has been studied for tactical military vehicles, naval vessels, and military installations (Dixon 1981, Griggs and Schanche 1992, Fink 2001). However, there is still a need for a comprehensive study focusing on recovery and repurposing of heat from tactical generator and other contingency basing utility systems. This literature review concentrated on the combination of two topics: WHR, and existing military equipment used for contingency basing. Primary sources included DTIC, ASPdb, the ERDC online technical library, professional technical journals, and technical specifications from manufacturers.

Much of the WHR technology in use today operates on a much larger scale (i.e., power stations or marine engines) than that found in CBs. Micro combined heat and power generation (CHP) systems with nameplate electric power generator output usually in the 1 to 100-kW range are more appropriately sized for use at CBs. Technologies used in micro-CHP include: internal combustion engines, micro gas turbines, Rankine cycle engines, Stirling engines, and fuel cells. The level of development or "maturity" of these technologies varies considerably (Bianchi 2014); not all are appropriate for application at CBs. In fact, the literature review did not locate much information on WHR on a tactical size applicable to contingency basing. Current information, summarized in the following paragraphs, generally describe prototype designs or proposals.

A study of a prototype WHR system using a 5-kW generator has shown that a possible fuel savings of 1500 to 2000 gallons per year with a 20 to 35% increase in fuel use can be realized resulting in the ability to provide 10 to 20 5-gal showers during every 5 hours of operation. The prototype system uses the exhaust heat from a 5-kW Advanced Medium Mobile Power Sources (AMMPS) to help heat the water in a 50-gal gas water heater. The Army plans to replace the Tactical Quiet Generators (TQGs), of which more than 79,000 are currently in use, with the AMMPS—so the potential payback from using this system is tremendous. However, an extensive analysis of the energy savings potential and best practices for use as a function of base size and climate would be required to develop practical recommendations for Soldiers and military planners (Tamm et al. 2014).

One proposed alternative to using ECUs powered by diesel electric generators is the use of a CHP system using a smaller engine and a lithium bromide/water (LiBr/H_2O) absorption system. Rather than using high energy-consuming compressors to pressurize refrigerant vapor, the chemical properties of Li/Br allow the absorption systems to pump it as a liquid to higher pressure. Experimental modeling results indicate that a LiBr/Water absorption system using a 3-kW tactical generator has the potential to achieve a 38% savings in fuel, 19% reduction in weight, and 4% reduction in physical size compared to conventional legacy systems. Further study and testing is needed to validate the system's performance under different simulation profiles before the development of an actual physical product (Horvath 2012).

Packaged 5-ton gas engine-driven heat pumps have been developed with electric generation and water heating capabilities that operate solely on natural gas with no power supply from the grid. These units can provide cooling or heating while simultaneously generating external electrical power for lights, computer equipment, and their internal motors; they can also recover waste heat for water heating. Coolant from the unit's internal combustion engine removes heat from the engine block and head and also recovers waste heat from the exhaust, which is then used to heat domestic water. A proof-of-concept version of this heat pump using JP8 fuel has been developed and tested to demonstrate the capability to simultaneously provide cooling, produce hot water, and generate 1 kW of electrical power (IntelliChoice Energy 2013).

Micro-CHP systems can use different technologies including internal combustion engines, Stirling engines, and organic Rankine cycles (ORCs), but the electrical efficiency of engines that are suitable for household-scale systems is relatively low. A proposed integrated advanced dual-cycle power system uses a thermoelectric generator to convert combustion heat directly into electricity; the ORC would recover a large portion of the remaining low temperature thermal energy to further increase the electricity production and the overall efficiency of the system. Test results from an experimental setup showed that thermoelectric power output could reach about 22% of the overall system output, significantly supplementing power to the micro-CHP system (Qiu 2012).

Micro-CHP units suitable for use in residential (single-family and apartment size) applications are commercially available, and may eventually replace conventional systems as they become more economical. Three commercial and one pre-production micro-CHP units were tested on their performance in producing electricity while generating and supplying heat. The units were studied under both steady and unsteady state operation. The steady state tests examined performance and emissions over a wide range of operating parameters including flow velocity in the heating circuit, and return and supply temperatures. Unsteady state tests looked at analyses of start-stop behavior and operation in combination with a hot water storage tank. The results found that the units were well developed and performed efficiently (Thomas 2008).

Fuel cells have the potential and capability to be used in CHP systems since they produce usable heat as a by-product of exothermic and electrochemical reactions. The cells have the potential to be used in applications requiring electrical power ranging from a few hundreds of milliwatts (mW) up to megawatt (MW) sizes. Fuel cell CHP systems can achieve higher overall efficiencies than other available CHP technologies at small scale power applications. In residential and small commercial applications, the most suitable and commonly used fuel cell technologies are polymer electrolyte membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFCs). The biggest drawback to fuel cell CHP systems are their high initial investment cost and strong market competition from competing CHP technologies. Additionally, the lack of proven durability compared to conventional technologies has limited fuel cell implementation. These factors should improve as the usage of these systems becomes more widespread (Ellamla 2015).

3 Analytical Approach and Waste Heat Recovery Opportunities

3.1 Contingency basing operations and application areas

3.1.1 Base camp sizes*

3.1.1.1 Basic

Basic capabilities are established as part of initial entry and are implemented primarily using organic capabilities and prepositioned stocks. Basic capabilities are those functions and services that are considered essential for sustaining operations for a minimum of 60 days. Basic capabilities are characterized by rapid deployment and emplacement. Basic facilities and infrastructure are highly flexible and moveable.

3.1.1.2 Expanded

Expanded capabilities are basic capabilities that have been improved to increase efficiencies in the provision of base camp support and services, and expanded to sustain operations for a minimum of 180 days. For example, a prime power system may be installed, a water bottling plant may replace imported bottled water, or an existing facility may be upgraded to replace tents. Engineer units or contracted support may be used to achieve the desired results. See HQDA (2011) for more information on contracted support.

3.1.2 Application areas (or function areas)

One area where energy demands can be reduced through the use of WHR is in water heating. In a 50 PAX base camp, the quality of life (QOL) level is typically basic and does not always include heated water services. In such a scenario, it would be possible to implement a simple water heating system for small amounts of heated water to be used for personal hygiene. In a 300 PAX camp the QOL level is expanded to include services that require heated water. Approximately 5600 gallons per day of heated water are used for a 300 PAX camp. Waste heat can be used to supply energy for a hot water storage system.

* Information in this section was drawn from HQDA (2013).

Tables 1 and 2 list quick reference estimates for quantities of various hot water applications that could be realized from waste heat recovery from several different generators. The theoretical waste heat available is calculated based on the measured efficiency and the generator loading. The available power is calculated according to the principles discussed in Section II-b-ii-2, where weather data for a moderate climate was averaged over a year period. The resulting value was used to determine a volume of water that could be heated from 10 to 90 °C (50 to 194 °F). In translating this to specific applications the following assumption of water consumption were used: showers are 5 minutes at 2.5 gal/min at 110°F; shaves are 2 minutes at 2.5 gal/min at 110°F; laundry uses 27 gal/load at 140°F; and coffee uses 3.8 gal/pot at 190°F. Fuel savings are extrapolated out to a year's period by assuming that energy recovered relieves the burning of fuel that contains an equal amount of energy (according the fuel heat of combustion of 36 kW-hr/gal).

Another area, which represents the largest consumer of energy, is space heating and cooling. Currently, FOBs use ECUs to control temperatures in shelter and other facilities; however ECUs require a significant portion of the energy produced by the generator to do so. A large amount of heat energy is lost to the exhaust stream of generators. Directly using this waste heat for environmental control of facilities represents huge potential for energy and fuel savings. Waste heat can be used to heat facilities, or with the use of absorption chillers, to provide space cooling to facilities.

3.2 Heat sources

3.2.1 Tactical generators

The main waste heat source considered in this study is the exhaust stream of generators of rated loads 10 kW, 15 kW, 30 kW, and 60 kW. Both TQG and AMMPS generators were studied, by using available exhaust data (Willis 2014), which include all the generators listed in Table 3 (excluding 15-kW TQG) operated at various loads.

Table 1. Summary of first order approximations for uses of waste heat from various sizes and loadings of TQG generators.

Generator Size TQG	%Load	Theoretical Waste Heat Available (kW)	Practical Waste Heat Available (kW)	Thermo Energy Storage (gal. water/hr heated to 190 °F)	Applications (#/day)	Fuel Savings (gal per yr)	Capital Cost ($)
5 kW	25%	10	3.6	10	48 Showers, 119 shaves, 15 loads of laundry, or 68 pots of coffee	873	$17,000
	50%	12	4.5	13	60 Showers, 149 shaves, 19 loads of laundry, or 86 pots of coffee	1093	
	75%	14	5.8	17	77 Showers, 191 shaves, 24 loads of laundry, or 110 pots of coffee	1400	
	100%	15	7.1	20	94 Showers, 235 shaves, 29 loads of laundry, or 135 pots of coffee	1720	
10 kW	25%	16	5.0	14	66 Showers, 166 shaves, 21 loads of laundry, or 95 pots of coffee	1212	$20,000
	50%	17	6.2	18	82 Showers, 204 shaves, 25 loads of laundry, or 117 pots of coffee	1495	
	75%	21	7.5	22	99 Showers, 248 shaves, 31 loads of laundry, or 142 pots of coffee	1815	
	100%	25	9.1	26	121 Showers, 303 shaves, 38 loads of laundry, or 173 pots of coffee	2215	
15 kW	25%	24	4.0	12	53 Showers, 132 shaves, 16 loads of laundry, or 76 pots of coffee	964	$20,000
	50%	28	5.3	15	70 Showers, 176 shaves, 22 loads of laundry, or 101 pots of coffee	1289	
	75%	34	6.8	20	91 Showers, 227 shaves, 28 loads of laundry, or 130 pots of coffee	1659	
	100%	39	8.6	25	114 Showers, 285 shaves, 35 loads of laundry, or 164 pots of coffee	2088	
30 kW	25%	37	12.7	36	168 Showers, 420 shaves, 52 loads of laundry, or 241 pots of coffee	3078	$35,000
	50%	47	16.2	46	215 Showers, 536 shaves, 67 loads of laundry, or 308 pots of coffee	3926	
	75%	58	20.3	58	269 Showers, 673 shaves, 84 loads of laundry, or 386 pots of coffee	4928	
	100%	70	23.8	68	316 Showers, 791 shaves, 98 loads of laundry, or 453 pots of coffee	5789	
60 kW	25%	57	14.7	42	195 Showers, 488 shaves, 61 loads of laundry, or 280 pots of coffee	3569	$35,000
	50%	72	20.5	59	272 Showers, 680 shaves, 84 loads of laundry, or 390 pots of coffee	4975	
	75%	98	27.5	79	365 Showers, 913 shaves, 113 loads of laundry, or 524 pots of coffee	6685	
	100%	119	36.0	103	478 Showers, 1194 shaves, 148 loads of laundry, or 685 pots of coffee	8740	

Table 2. Summary of first order approximations for uses of waste heat from various sizes and loadings of AMMPS generators.

Generator Size AMMPS	%Load	Theoretical Waste Heat Available (kW)	Practical Waste Heat Available (kW)	Thermo Energy Storage (gal. water/hr heated to 190 °F)	Applications (#/day)	Fuel Savings (gal per yr)	Capital Cost ($)
5 kW	25%	8	1.9	5	26 Showers, 64 shaves, 8 loads of laundry, or 37 pots of coffee	469	$17,000
	50%	9	2.4	7	32 Showers, 79 shaves, 10 loads of laundry, or 45 pots of coffee	578	
	75%	10	2.9	8	39 Showers, 96 shaves, 12 loads of laundry, or 55 pots of coffee	705	
	100%	11	3.5	10	47 Showers, 117 shaves, 14 loads of laundry, or 67 pots of coffee	853	
10 kW	25%	10	3.8	11	50 Showers, 126 shaves, 16 loads of laundry, or 72 pots of coffee	919	$20,000
	50%	12	5.0	14	67 Showers, 167 shaves, 21 loads of laundry, or 96 pots of coffee	1223	
	75%	15	6.6	19	88 Showers, 219 shaves, 27 loads of laundry, or 125 pots of coffee	1602	
	100%	17	8.3	24	110 Showers, 274 shaves, 34 loads of laundry, or 157 pots of coffee	2004	
15 kW	25%	13	5.4	16	71 Showers, 178 shaves, 22 loads of laundry, or 102 pots of coffee	1306	$20,000
	50%	16	7.3	21	96 Showers, 241 shaves, 30 loads of laundry, or 138 pots of coffee	1765	
	75%	21	9.6	28	127 Showers, 318 shaves, 40 loads of laundry, or 182 pots of coffee	2329	
	100%	23	12.1	35	161 Showers, 402 shaves, 50 loads of laundry, or 230 pots of coffee	2941	
30 kW	25%	25	9.6	28	128 Showers, 319 shaves, 40 loads of laundry, or 183 pots of coffee	2335	$35,000
	50%	29	13.8	14	183 Showers, 458 shaves, 57 loads of laundry, or 262 pots of coffee	3350	
	75%	42	19.7	56	262 Showers, 655 shaves, 81 loads of laundry, or 376 pots of coffee	4795	
	100%	59	29.3	84	389 Showers, 972 shaves, 121 loads of laundry, or 558 pots of coffee	7119	
60 kW	25%	42	17.1	49	226 Showers, 566 shaves, 70 loads of laundry, or 325 pots of coffee	4144	$35,000
	50%	59	28.0	80	372 Showers, 930 shaves, 115 loads of laundry, or 533 pots of coffee	6810	
	75%	82	41.7	120	554 Showers, 1385 shaves, 172 loads of laundry, or 794 pots of coffee	10136	
	100%	101	50.7	145	673 Showers, 1682 shaves, 209 loads of laundry, or 964 pots of coffee	12310	

3.2.2 Thermodynamic analysis

3.2.2.1 Theoretical energy available

Theoretical energy available from various generators was calculated using available exhaust data. Ambient temperatures of the test conditions when the exhaust data were collected ranged from 13 to 33 °C (55.4 to 91.4 °F). Exhaust temperature with exhaust volumetric flow rate, normalized to standard conditions, were reported. Weather files used in simulations included temperatures outside of the range of the above testing conditions, at both extremes. Although some differences in the exhaust temperature and volumetric flow rates are expected for different climates, these differences are expected to be insignificant to the overall analysis such that neglecting to account for such changes would have minimal impact on the final results.

Table 3. Generators considered in this study.

Set Size	Generator, Model No.	
	AMMPS	TQG
10 kW	MEP-1040	MEP-803A
15 kW	MEP-1050	MEP-804B (no data available)
30 kW	MEP-1060	MEP-805B
60 kW	MEP-1070	MEP-806B

The theoretical maximum extractable energy using a heat exchanger is determined from the greatest temperature difference between the two fluids of the heat exchanger and the minimum of the product of mass flow rate, $\dot{m}$, and specific heat capacity, c_p (Holman 2002). In this study's simulations, the exhaust typically had the minimum value of $\dot{m}\ c_p$. The theoretically available power can then be calculated from the exhaust data for each generator by:

$$\dot{m} = Q_s \rho_{stp} \quad (3\text{-}1)$$

$$P_{theor} = \dot{m}\ c_p\ \Delta T_{max} \quad (3\text{-}2)$$

In Equations 3-1 and 3-2, Q_s is the standardized volumetric flowrate; ρ_{stp} is the exhaust density at the associated standard conditions; and ΔT_{max} is the maximum temperature difference in the system, which represents the difference in temperature between the two fluids at the heat exchanger inlet.

The chemical composition of the generator exhaust was approximated to be 67% nitrogen (N_2), 12% carbon dioxide (CO_2), 11% water vapor (H_2O), and 10% oxygen (O_2). For the purposes of calculating fluid properties, trace elements present in quantities of <1% were neglected. These percentages were based on exhaust composition from diesel engine exhaust of automobiles (Volkswagen Group 2000). Density and specific heat capacity were determined using tabulated data for each of the constituent gases and employing a rule of mixtures, weighted by volume percent to determine density and weighted by mass percent to determine specific heat capacity.

Exhaust data vary significantly for each generator depending on the electric load placed on it. Generator and equipment layouts require that peak loads do not exceed the maximum rated load for the generator; however, peak loads represent a small percentage of operating time. Based on meter data collected during training exercises and reports from units deployed in Afghanistan, typical operation occurs with a baseline of about 30% loading (Johannes and Decker 2014). Although actual loading fluctuates around the baseline load, the simulations approximate the generators loadings as constant. Simulations were run for 10%, 25%, 50%, 75%, and 100% loadings.

As mentioned earlier, a typical TOC has a load requirement of 16 to 20 kW. Of this, 11 kW is reserved for the Improved ECU (iECU) data plate rating. Test data show that the iECU has the following power requirements: 10.2 kW in "heating mode," 6.2 kW in "cooling mode," and 1.2 kW in "vent mode." Therefore, if the unit is operating in heating mode, the generator is oversized by 800 watts, operating in cooling mode the generator is oversized by 4.8 kW; when operating in vent mode, the generator is oversized by 9.8 kW per iECU connected. It is expected that the implementation of WHR systems would reduce the difference between peak and baseline loading, allowing the baseline operation to occur at a higher load, and consequently operate the generator at a higher efficiency.

3.2.2.2 Practical energy available

The practical energy available depends on the efficiency of components used to extract and transport heat. The energy available from the generator exhaust is only useful to the extent that it can be transported and/or converted to other forms of energy. The first step is to use a heat exchanger to transfer the energy from the exhaust to the working fluid. Heat exchanger effectiveness, $\in$, is a metric used to determine the amount of

heat that can be transferred with a given heat exchanger setup. It is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. As noted above the maximum heat transfer is $\dot{m}\, c_p\, \Delta T_{max}$. Then the practical available heat is given by:

$$P_{practical} = \in \cdot\, \dot{m}\, c_p\, \Delta T_{max} \tag{3-3}$$

Heat loss due to transport between components was calculated using Nusselt number (Nu) correlations for horizontal cylinders for the convective heat transfer inside and outside of the pipes. A correlation recommended by Dittus and Boelter (1985) was used for the internal flow of the water in the pipes, and a correlation given by Churchill and Bernstein (1977) was used for the exterior flow of the air past the pipes (Holman 2002). Wind speed data were used for exterior flow properties while the interior flow was assumed to be constant. Temperature dependent properties for water and air were used, with the conductivity of the pipe and insulation materials treated as constant.

3.2.3 Other sources and considerations

3.2.3.1 Incinerators, gasifiers, and pyrolyzers

Although significant waste heat is produced by generators, there are other potential sources on FOBs where waste heat might be recovered. As with generators, the exhaust is high temperature, and can be at flow rates comparable to a generator. For instance, the incinerators used for trash disposal produce copious amounts of thermal energy during the combustion process, usually at temperatures of at least 850 °C (1,562 °F). Although not considered specifically in this study, recovery of thermal energy from incinerators is an ideal complement to thermal energy recovery from generators, as they both have very steady fuel streams. Moreover, any energy recovered from an incinerator is a net gain because, currently, non-recyclable refuse/trash has no other potential use. One issue that should be noted is that incinerators are usually kept away from buildings and structures due to safety concerns, so any waste heat recovered would have to be transported further than would heat from a generator, which leads to increased line losses and increased thermal distribution system complexity (e.g., the use of steam).

In addition to incinerators, both gasifiers and pyrolyzers are Waste-to-Energy (WtE) options for FOBs. These devices also produce copious amounts of heat during the non-combustive waste destruction process. Pyrolyzers

convert volatile organic waste into combustible fuels (syngas) and non-volatile ash. The process occurs without oxygen, at temperatures of 200 to 760 °C (400 to 1,400 °F). Gasification goes one step beyond pyrolysis in that it also converts the non-volatile ash normally resulting from pyrolysis into additional syngas fuel. Gasification occurs at even higher temperatures, 480 to 1,650 °C (900 to 3,000 °F), also without oxygen. As with incinerators, these devices are typically kept away from buildings for safety purposes, so line losses are a problem. Moreover, most pyrolyzers and gasifiers use a portion of the exhaust heat to preheat the incoming waste and remove water, which lowers the available thermal energy that can be recovered. Nonetheless, as all of these technologies become more prevalent in place of burn pits, additional opportunities for waste heat reuse will become available.

3.2.3.2 Drain water

Greywater is another potential source of heat recovery. In household use, this method is often used as a way to preheat cold water to increase hot water capacity. Typically 80 to 90% of the energy used to heat water is literally sent down the drain (DOE 2012). If the Greywater is drained through a heat exchanger, some of that energy can be recovered. This approach could be employed in Army camps to send preheated water into the hot water storage tank to replace consumed hot water, thus reducing the hot water heating demand.

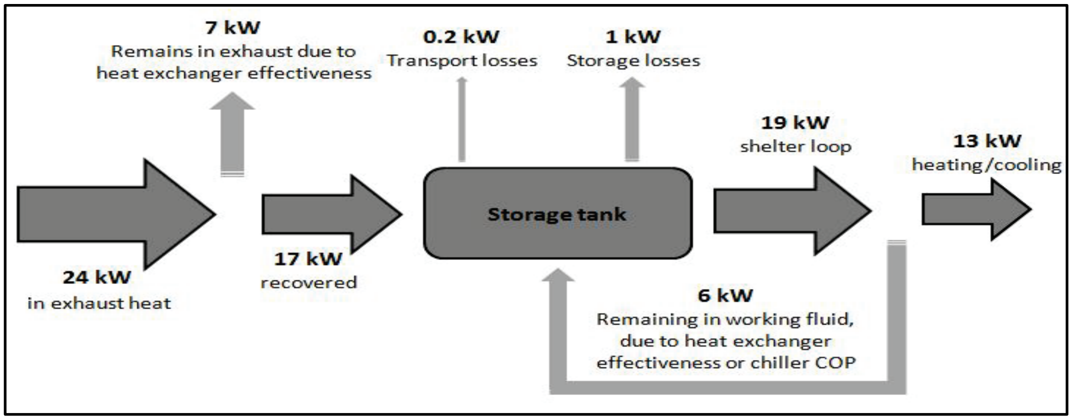
3.3 Heat uses

3.3.1 Space heating and cooling

Using of waste heat to provide space heating in shelters is the most practical application; it allows for more direct use of the recovered energy, which reduces inefficiencies associated with conversion between different types of energy (i.e., heat to electric and back to heat). Additionally, cooling energy can be provided from the waste heat through the use of absorption chilling. Typically compression chillers are preferred since they are more efficient than absorption chillers. However, compression would require the use of electricity and thus conversion losses would negate the benefits. Additionally, technology advances are pushing toward high efficiency adsorption cooling systems (PNNL 2015), and adsorption chillers can use water as the refrigerant. Because environmental control of the shelters consumes the majority of energy needs, WHR for heating and cooling represents signifi-

cant potential to reduce energy demands. Figure 2 shows a flowchart of approximate power values when waste heat from a 60-kW generator operating at 50% load is used to supply heating and cooling needs.

Figure 2. Power flow chart for WHR used to supply heating and cooling, from a 60-kW generator operating at 50% load.



In general, two types of shelters are used in base camps: soft shelters and hard shelters. AirBeam tents and B-Huts were chosen to represent each of these types of shelters, respectively, due to their common use in-theater. The heating and cooling demands for each of the chosen shelters were determined using DoD's EnergyPlus software. (The AirBeam model was obtained from the National Renewable Energy Laboratory (NREL) and the B-Hut model was obtained from the Oak Ridge National Laboratory [ORNL].) Simulations were run with weather files for several locations selected to represent each of four climate regions: desert, rain forest, temperate, and arctic. Indoor temperature set points were 23 °C (74 °F) and 20 °C (68 °F) for cooling and heating, respectively.

AirBeam shelters are tents with a thick exterior covering supported by pressurized air beams that are inflated simultaneously using an air compressor. They have internal linings that create a thermal barrier gap, and a plenum that supports use of Environmental Control Units (ECU). The available sizes vary, but the AirBeam model used for this study is a 6 x 10-m (20 x 32-ft) structure.

B-Huts are a type of temporary shelter typically constructed with a basic wood frame and plywood walls with dimensions 5 x 10 x 2 m (16 x 32 x 8 ft). The truss roof can be covered with metal or plywood. The structure is placed on wood piers set on a gravel base. Some B-Huts are constructed

with concrete masonry units (CMUs). These shelters are not typically insulated and usually have large amounts of air infiltration, leading to poor overall energy efficiency. Although work is being done to improve the building practices for these huts to increase their energy efficiency (Pagan-Vasquez 2015), the B-Hut model used in this study represents the baseline wood structure.

Both types of shelters typically use Army supplied ECUs for heating and cooling. Since heating and cooling constitute the major portion of power demands in camp operations, the ability to remove ECUs and replace them with waste heat supplied heating and cooling would significantly reduce energy (and thus fuel) demands. In the TOC example (p 1), the removal of an iECU, with data plate rating of 11 kW, would reduce energy consumption by 55 to 68% of the 16 to 20 kW typically required to operate the facility.

To quantify the extent to which heating and cooling demands can be met with recovered heat energy, simulations for various generators at each of the selected locations were compared with the corresponding EnergyPlus™ simulations for each of the shelters (Table 4). The heating and cooling demands were compared to the end-use power available for either heating or cooling, and the percentage of the overall required power that could be supplied was calculated. During hours where supply exceeded demand, the excess power did not factor into the overall percentage. Those results were then averaged across the respective climate regions.

Table 4 lists the results for each of the generator and climate region combinations for the B-Hut; Table 5 lists the same results for the AirBeam shelter. The data are color coded: green indicates that an average of better that 90% of the heating and cooling demand can be supplied throughout the year; yellow indicates between 80 and 90%; and red indicates below 80%.

Table 4. The percent of heating and cooling demands for a B-Hut that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions.

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	78.57%	13.30%	86.48%	4.32%	91.26%	3.73%	90.83%	3.37%
15kW AMMPS	87.60%	13.80%	95.01%	2.36%	98.33%	0.89%	96.76%	2.44%
30kW AMMPS	95.04%	10.11%	99.90%	0.12%	99.99%	0.01%	99.67%	0.50%
60kW AMMPS	98.82%	2.61%	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%
10kW TQG	83.95%	13.79%	91.63%	3.25%	96.16%	1.73%	94.63%	2.95%

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
30kW TQG	96.14%	8.32%	99.99%	0.02%	99.99%	0.01%	99.84%	0.28%
60kW TQG	97.35%	5.87%	100.00%	0.00%	100.00%	0.00%	99.95%	0.10%

Table 5. The percent of heating and cooling demands for an AirBeam tent that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	89.51%	8.76%	92.12%	2.48%	91.38%	2.02%	94.76%	1.26%
15kW AMMPS	96.43%	5.81%	98.65%	0.96%	99.42%	0.40%	99.54%	0.27%
30kW AMMPS	99.93%	0.14%	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%
60kW AMMPS	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%
10kW TQG	93.84%	7.28%	96.34%	1.64%	96.95%	1.23%	98.13%	0.71%
30kW TQG	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%
60kW TQG	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%

The results indicate that, for both shelters and in all climates, cogeneration is very promising for both 30 and 60-kW generators. For both sizes, in all locations, 100% of the AirBeam demand can be supplied, and at least 96% of B-Hut demand can be supplied. For the non-arctic regions, at least 99.8% of B-Hut demand can be supplied. Further calculations carried out for these generators show that two shelters can be supplied with more than 90% of their demand in all locations for AirBeam tents, and all but arctic locations for B-Huts (see Appendix A). For B-Huts in arctic locations, the supply averaged about 90% of demand, but with about 12% standard deviation. Thus, for B-Huts in arctic locations, a significant amount of energy would need to augment to the cogeneration system to meet heating needs. In some scenarios, more than 90% of the heating and cooling demands of three and four shelters can be supplied.

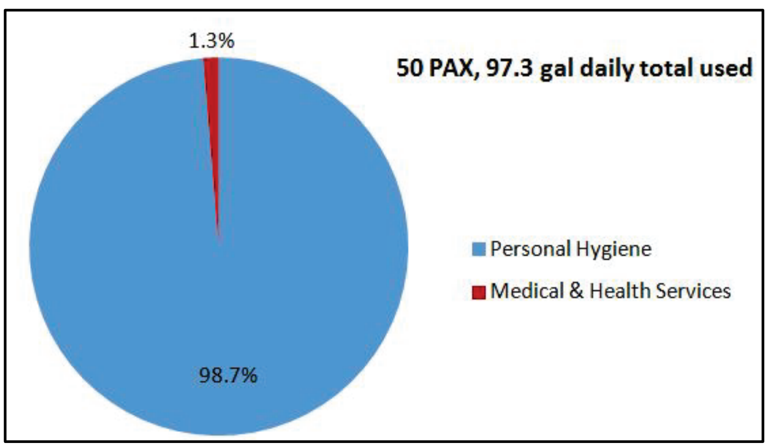
3.3.2 Water heating

In a 50 PAX base camp, the QOL level is typically basic and does not always include heated water services. Figure 3a shows average daily water usage. In such a scenario, it would be possible to incorporate a simple water heating system for small amounts of heated water to be used for personal hygiene. Such a system would consist of a small reservoir of supply water, a pump, and a heat exchanger connected to the generator exhaust. A small amount of water could be pumped through the heat exchanger as needed, similar in

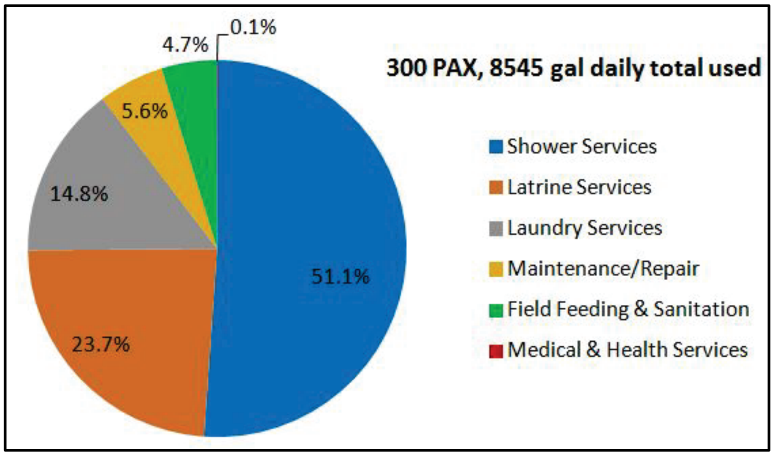
concept to tank-less water heating systems used in homes. Simulations predict that a 30-kW generator operating at 50% load is enough to supply 1.75 gpm of instantaneous hot water at 40 °C (104 °F) from a 10 °C (50 °F) supply of cold water. Thus, each 30-kW generator could provide enough hot water for a shower in austere conditions (water supply permitting). This assumes a heat exchanger effectiveness of 0.7 and is relatively insensitive to the outdoor air temperature. It is, however sensitive to the temperature of the water supply, which has been assumed to be constant.

In a 300 PAX camp the QOL level is expanded to include services that require heated water (mostly showers and laundry services, see Figure 3b). For a hot water storage system, simulations indicate that the waste heat from one 60-kW TQG operating at 50% of rated load in an arctic environment could supply random amounts of hot water at up to 50 gpm, for 1-minute intervals, from a 500 gal tank. Such usage leads to an average daily supply of about 1,270 gal, while maintaining hot water in the range of 60 to 65 °C (140 to 149 °F). The energy required to supply that volume of hot water is approximately 270 kWh, which translates to about 11.5 kW of average power. For a 300 PAX base camp, this represents about 22% of the average daily volume of heated water used.

Figure 3. Average water usage for 300 PAX and 50 PAX camps.



a.



b.

Source: Anderson et al. (2013).

If a larger temperature range is tolerable for the storage tank, larger volumes of heated water could be realized; however that may contribute to the risks noted below. Note that the limiting factors include a combination of the amount of energy available to heat the water, the allowable temperatures, usage flow rates, and tank size. It would be possible in some of the scenarios using 60-kW generators to supply space heating and cooling, while also supplying a portion of a base camp's hot water.

3.3.2.1 Safety

Risks associated with hot water storage include two somewhat conflicting concerns: (1) Risk of exposure to Legionella bacteria is increased in locations where water temperature is too low, yet, (2) risk of scalding increases with hotter storage temperatures. To prevent growth of Legionella, it is recommended to keep water heaters at a minimum of 60 °C (140 °F) and to keep water delivered at the faucet at a minimum of 50 °C (122 °F) (OSHA 2014). However, at 50 °C (122 °F) the risk of scalding is significant; the exposure time for a first degree burn is 1 minute and for a second degree burn is 5 minutes (ASSE 2012). To prevent scalding risk, it is recommended to use some sort of mixing valve at the point of hot water delivery.

3.3.3 Other

3.3.3.1 Electricity generation

In circumstances where need for thermal energy is low, overall efficiency of electricity generation could be improved by using the generator waste heat

to produce more electricity, through the use of various heat cycles. Most notably, ORCs are promising for this type of power generation. A feasibility study was conducted by DiCarlo and Wallace (DiCarlo 2011) for the use of an organic Rankine cycle system coupled to the exhaust of a 78-kW diesel generator. They reported a maximum ORC thermal efficiency of 14.3% and 5.36 kW of net electrical power generated. Current technology on the market is capable of producing 10 to 20% additional power from generator waste heat, without need for additional fuel (EthosGen 2015).

Other means for generating electricity from waste heat are also possible. Aladayleh (2015) demonstrated the use of Stirling engines to produce electric power from waste heat from an internal combustion engine. Incorporation of thermoelectric power cycles can be coupled to combustion generated power generation to improve overall performance (Qiu 2012). Note that a separate DOTMLPF assessment should be conducted on these application for a CB environment.

In general, a better route to generate additional electricity is simply to ramp up the generator. The Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) has evaluated this application in the past using hydrogen storage and fuel cells (Holcomb et al. 2007), which can be cost (and energy) effective when shutting down the generator in times of low demand (generally at night). This concept was dubbed Silent Camp™; a similar approach to electricity storage could be achieved using battery technology. Technical and cost analysis using WHR technology incorporated with the Tesla Powerwall is further explained in the Analysis (by generator configuration) (Section 3.5, p 29).

3.3.3.2 Wastewater treatment

Waste heat can also be used to accelerate the biodegradation of organic contaminants in conventional and emerging wastewater treatment processes. For conventional aerobic bioreactors or biofilters, performance decreases at lower temperatures, which requires longer hold times or larger reactors (Tchobanoglous, Burton, and Stensel 2003). Alternatively, waste heat from generators could be used to heat the wastewater before treatment in conjunction with heat exchangers and thermal insulation around the reactor to reduce heating requirements. Calculations demonstrate that about 44 W-hrs are required to heat a gallon of water by 10 °C (50 °F). Thus, a 60-kW electrical output generator that is putting off 30% of its fuel energy content (40 kW) as recoverable heat could heat nearly 22 kgal per

day to increase the temperature by 10 °C (50 °F), without considering any heat recovery/exchange systems.

In future Army wastewater management frameworks for CBs, 22 kgal would represent the amount of wastewater from a 2000-PAX CB. A recent ERDC technical report (Feickert 2012) indicated that heat exchangers between the influent and effluent streams could reduce water heating requirements by about 50 to 70%, which would approximately double the heating capacity of a generator. Such an approach could be highly advantageous for accelerating wastewater treatment processes, particularly anaerobic processes, which function optimally at 35 °C (95 °F). Additionally, in arctic climates, thermal loads for keeping water lines and water tanks from freezing would be a beneficial opportunity for using waste heat.

3.3.3.3 Water vapor harvesting

The ability to augment the water supply by scavenging water from currently untreatable sources, from moisture-laden materials such as soil and sludge, or directly from air via desiccation and/or efficient phase change processes is desirable. Unfortunately, phase change processes are generally energy intensive, as evidenced by the high fuel requirements of current Army atmospheric water generator (AWG) technology. In the indoor pool industry, heat pump technology is used to dehumidify air (collect water vapor) from the atmosphere and direct the energy of condensation on the cooling coil to the water heater to offset fuel requirements for water heating. This is a simple principle that can potentially be exploited for a wide range of AWG applications.

Given a heating requirement and/or a currently wasted heat source (i.e., electricity generators or waste incinerators), heat pumps could be used to more efficiently recover water vapor from a broad range of sources, including reverse osmosis brine evaporation ponds, sludge drying beds, desiccants, or even soil. For instance, a heavily contaminated wastewater source such as a brine evaporation pool or a sludge drying bed could be heated to create a favorable humid air stream from which to extract water vapor.

Given that the generators at CBs liberate about 33% of their fuel content as recoverable waste heat, there would be plentiful energy available to offset evaporative and wastewater losses at a CB if practical systems can be developed. For example, one 60-kW generator at 50% load consumes about 3 gallons of fuel per hour and would provide about 40 kW-hr of recoverable

waste heat. Assuming 75% of this is diverted to a water vapor source, it could liberate about 20 gallons per hour (gph) of water into the air, assuming typical commercial drying efficiencies are achieved. However, by recovering and reusing the heat of condensation at an efficiency value of 75%, the energy available for water vaporization would be closer to 60 kWh, liberating 30 gph. Theoretically, the waste heat from a single 60-kW generator operating at 50% load could produce 720 gallons of clean water per day.

3.4 Heat recovery system components

3.4.1 Heat exchangers

3.4.1.1 Air to liquid

The most important component in the WHR system is the heat exchanger used to recover heat from the waste heat stream. The prototype designed as part of this study uses a cross-flow gas-to-liquid heat exchanger. Fouling of the heat exchanger is a common problem in recovering waste heat. Chemicals in the exhaust stream can interact with the materials in the heat exchanger and deposits can build up on the heat transfer surfaces, reducing heat transfer rates and ultimately the effectiveness of the heat exchanger (DOE 2008).

It is unclear how the selected heat exchangers will be affected by fouling, however proper consideration can prevent major problems from arising. Common methods for dealing with fouling involve prevention (i.e., proper design of the heat exchanger), or maintenance (i.e., cleaning). Although the current design allows easy access to the heat exchanger for cleaning, a system that requires less maintenance would allow Soldiers to spend more time on more important tasks. When space heating the shelters, a second heat exchanger with a blower fan will be used. The use of a heat exchanger to transfer heat from the hot water to the ambient air will make the exchanger much less susceptible to fouling.

3.4.1.2 Liquid to liquid

It is possible that future designs would incorporate alternative working fluids, which, in a water heating application, would require an additional heat exchanger between the working fluid and the heated water. This would result in additional losses between the waste heat stream and the heated water supply. Any alternative working fluids used must present greater capacity for recovering heat beyond these additional losses.

As noted, the use of Greywater heat recovery can provide some relief from hot water energy demands. This would also require the use of liquid-to-liquid heat exchangers. Such a heat exchanger would replace a section of drain and allow incoming supply water to recover heat from the drain water.

3.4.1.3 Safety and control

The use of heat exchanger with the exhaust of generators will develop additional back-pressure on the exhaust line. Any additional obstructions (e.g., due to foreign objects or fouling) to the exhaust flow through the heat exchanger could introduce even greater back-pressure on the exhaust line. Safety concerns and risk of damage to the generators dictate that precautions be taken to prevent back-pressure from reaching critical levels. The prototype designs that this study investigated used an oversized fitting around the generator exhaust pipe to allow a path for venting to prevent high pressure buildup.

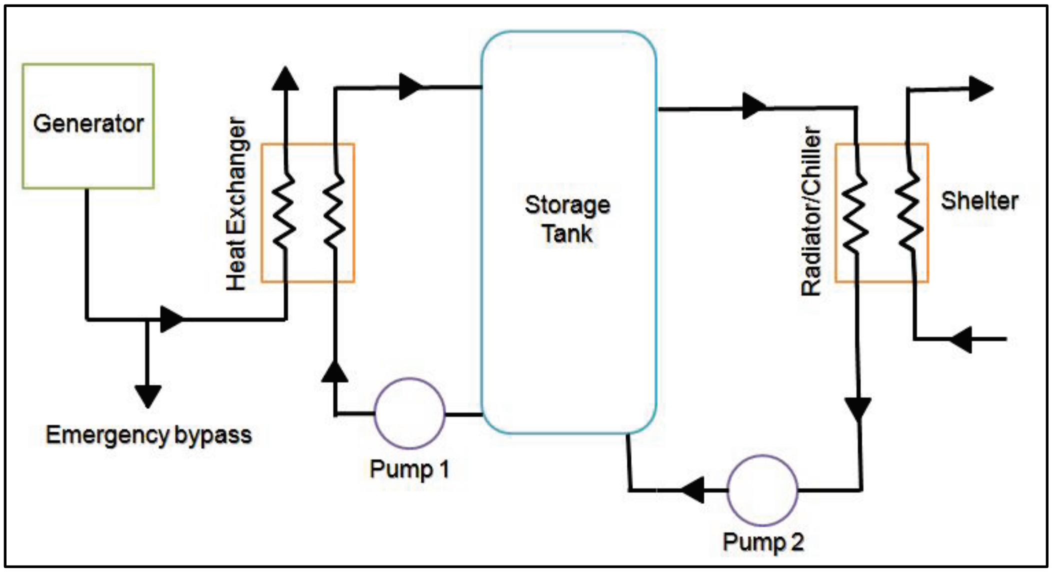
When water is used as the working fluid, water temperatures in the waste stream heat exchanger will be near boiling point; however, for safety reasons, it is desirable to keep the water from boiling. For an exhaust gas-water heater exchanger connected to the generator, it is critical to have a bypass route in place to allow the exhaust gas to vent away from the heat exchanger. This can be done either manually or by combining the water outlet with a temperature feedback system to provide automated control that works similarly to a thermostat in a combustion engine.

3.4.2 Thermal energy storage

3.4.2.1 Water

Water is readily available on contingency bases and can be used to transport thermal energy as a working fluid and to store energy through sensible heat gain. Figure 4 shows an example of a WHR system that uses water for thermal energy storage. A tank of water is connected to two loops. One loop cycles water from the tank through the exhaust heat exchanger, where the water temperature rises, and then back to the tank. The second loop cycles water from the tank either to an absorption chiller or to a radiative heater in the shelter, where the water temperature decreases, and then returns the water to the tank.

Figure 4. Schematic for generator WHR system



This process has a capacitive effect, allowing some energy to be stored while heating or cooling demands are low, and making it available quickly when demands are high. The storage capacity is limited by the total mass of water in the system, the temperature ratings of the tank and pipes, and the vaporization temperature of water (also discussed in Section 3.4.1, “Heat exchangers”).

A similar setup can be used for hot water applications, much like a water heater in a house. In this case, instead of a loop through the shelter heating or cooling component, hot water would be removed and consumed for various uses, and replaced with the same volume of cold water added to the storage tank.

3.4.2.2 Other liquids

One limitation to thermal storage, as mentioned above, is the vaporization temperature (boiling point) of water. For safety reasons, the heat recovery system is designed to keep the working fluid from boiling. Water has a relatively low boiling point ($c_p = 4.19$ kJ/kg-K), but its boiling could be increased significantly by mixing the water with ethylene glycol. The use of ethylene glycol, however, increases the complexity of the heat recovery system.

Requirements would include higher temperature materials for the pipes and storage tank, and a separate, isolated loop for water heating applications; a trade-off occurs with the specific heat of the mixture. For a 50%

mixture of ethylene glycol and water a specific heat capacity reduction of 15% would occur, which would require an 18% increase in the combination of mass and temperature difference ($m \cdot \Delta T$) to store the same amount of heat (c_p = 3.56 kJ/kg-K). This comes with an increase in boiling point to 107 °C (225 °F) and decrease in freezing point to -37 °C (-35 °F). Although higher temperatures could be reached before the fluid reaches the point where exhaust must be vented away from the heat exchanger, the capacity for storing heat would be diminished. Still, in climates where temperatures are too low for water, it may be worth the added complexity to use an ethylene glycol mixture to prevent freezing of the working fluid.

3.4.2.3 Phase change

As an alternative to either water or other conventionally used working fluids, it is worthwhile to consider the use of enhanced heat transfer fluids that can recover and store more thermal energy due to a phase change (liquid-solid). Phase change materials (PCMs) represent a promising class of materials for heat storage because they can be used to store thermal energy from the latent heat released during phase transition in addition to their specific heat capacity (C_p). However, despite this advantage, most PCMs have lower thermal conductivity (k) and specific heat capacity (both mass and volume specific) compared to pure water (Sharma et al. 2009). Also, in their native form, PCMs do not flow (because they are solid in their cold state) and would therefore clog the lines. To enable PCMs to flow, slurries have been developed containing microencapsulated PCM particles suspended in water (Delgado et al. 2012). For many PCMs, the limiting thermal-cycling windows are larger than the range for which water stays in liquid form. This means that many PCMs can store greater thermal energy than pure water, over the temperature range in which water takes in only sensible heat. The practical limit to the thermal-cycling window will be set by the boiling point of water (not accounted for here).

Results from modeling performed by the University of Illinois at Urbana-Champaign (UIUC) indicate that PCM slurries are useful for small thermal-cycling windows (<10 °C [<50 °F]), which are too small to merit use in heat recovery from diesel generators, considering that diesel-exhaust heat is available at T_H = 180 °C (356 °F) (Tamm et al. 2014) and room-temperature heat rejection would occur at T_C = 20 °C (68 °F). Using PCM slurries for larger thermal-cycling windows (in colder climates) requires large pressure drops with marginal increase in heat-storage capacity relative to liquid water. Alternatively, the large heat-storage capacities gained

by PCM slurries at low thermal-cycling windows could enable their use in reheating of hot water with waste hot water (~60 °C [~140 °F]).

3.4.2.4 Thermal mass

In regions where large diurnal temperature ranges occur, such as hot-dry climates, the use of thermal mass to induce a time lag in heat transfer between the outside and inside of a shelter can be beneficial. With careful sizing and orientation of thermal massing (e.g., masonry or earth), a time lag from the heating hours of the day to the cool times at night can be implemented to reduce the need for cooling during the day and provide some heating at night (Al-Homoud 2005). This practice could be used in combination with WHR to even further reduce energy demands of Army shelters. As mentioned (Section 3.3.1, p 16), some B-Huts are constructed with masonry. Additionally, earth could be piled up in certain areas to provide thermal mass.

3.4.2.5 Loss calculations

Any method of thermal storage will be subject to losses. For the method of sensible heat gain in water, simple loss calculations were implemented in the simulations. The overall heat transfer coefficient for the tank (U_{tank}), which considers the convective heat transfer inside and outside the tank, the tank material, and insulation surrounding the material, was calculated and combined with the surface area of the tank (A_{tank}) and temperature difference (ΔT) between the tank water and outdoor air to determine the heat loss, according to:

$$q_{loss} = U_{tank} A_{tank} \Delta T \tag{3-4}$$

3.4.3 Distribution and limitations

3.4.3.1 Materials

Transport of the working fluid varies in distance depending on the location of the generator in relation to the location where the recovered heat is being used or stored, but is on the order of tens of meters. The prototype uses flexible, cross-linked polyethylene (PEX) for the ease of installation. This material is commonly used in hot water applications in homes and other buildings. Outdoor applications, however, are limited due to the sensitivity of PEX to Ultraviolet (UV) exposure. It must remain shielded from any UV exposure to prevent deterioration and failure of the pipes. Ideally,

the pipe would be buried. This would provide sufficient cover from UV exposure as well as provide excellent insulation to reduce heat loss during transport. Any non-buried portion (e.g., at tank or heat exchanger connections) must be sufficiently insulated and shielded from sunlight. Temperature ranges near the boiling point of water represent the upper limit of PEX temperature ratings. The design tank is also made of polyethylene and has similar temperature limits.

3.4.3.2 Range limitation

Pumps will be required to move the working fluid in the heat recovery system. For a distance of 30 m and an elevation change of 1.5 m, approximately half of the required pumping power is due to friction losses, while the rest is due to minor losses and elevation change. The friction losses will increase linearly with the distance while the minor losses remain constant. An increase in distance transported could also affect the elevation change, depending on the terrain. Since required pumping power increases with distance and elevation change, pumps used must be properly sized for the desired spacing between shelter, tank, and generator. To avoid excessive friction losses, it would be beneficial to use recovered heat in shelters closest to the generator from which it is recovered.

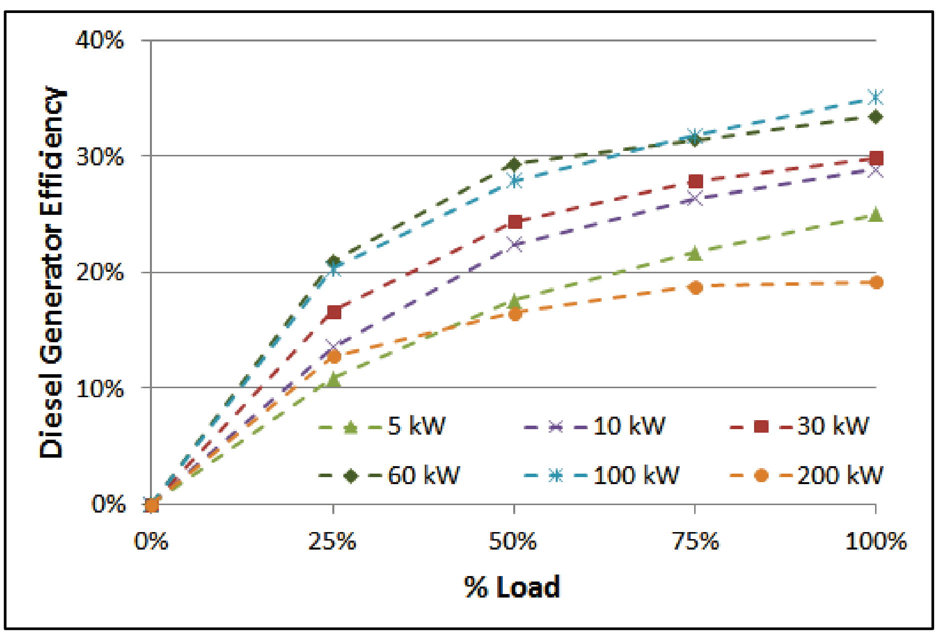
As indicated above, alternative working fluids will have different viscosity from water. In the case of phase change slurries, the viscosity is significantly greater. Additionally, the flow rate plays an important role in required pumping power. Higher flow rates will lead to higher friction losses in the pipes. This must be balanced with the temperature limits of the working fluid in the lines. For high exhaust temperatures and flow rates, it is desirable to have a higher working fluid flow rate so that its change in temperature across the exhaust heat exchanger is smaller. Then the inlet of the heat exchanger (thus the storage as well) can reach a higher temperature before the heat exchanger outlet exceeds the maximum allowable temperature, which in turn allows more heat to be recovered. Simulations indicate that a working fluid flow rate of 10 gpm is sufficient in most cases. For 60-kW generators operating at 100% load, a flow rate of 15 gpm results in significant improvement, but requires approximately double the pumping power. Flow rates beyond 15 gpm result in marginal improvement while requiring significant increases in pumping power. This is due to the quadratic relationship between fluid velocity and friction losses.

3.4.3.3 Load operation

A previous study used the Deployable Metering and Monitoring System (DMMS) to meter and monitor Operational Energy (OE) use at the Experimental Forward Operating Base (ExFOB). The results showed that average generator usage was 34.7% of capacity and peak usage was 43.2% (Johannes and Decker 2014), which is a low-efficiency mode of operation. As seen in Figure 5, a significant increase in generator efficiency is achieved for loads above 50% of capacity. Also, loads under 50% can lead to wet stacking and, over time, can damage the engine (ARCIC 2013).

The ability to remove some of the peak loads by using waste heat to supply heating and cooling would allow generators to be consolidated so they can operate more consistently at higher loads, and thus at higher efficiency with less damage. For example, if two shelters were connected to one 60-kW generator, allotting 5 kW each for outlet power and 11 kW each for their ECUs, then the generator would supply just over 50% of its rated load at peak operation, while the baseline operation is well below that. The use of waste heat to supply the heating and cooling to one of those shelters would reduce the peak load 21 kW, which would allow the generator to be downsized to 30 kW. Now, the peak operation for the 30-kW generator would be at 70% and the baseline would be close to 50%. The combination of downsizing the generator and increasing the generator efficiency would decrease fuel demand.

Figure 5. Diesel generator efficiency as a function of load for generators rated from 5-200-kW output, running on Diesel-2 fuel.



Alternatively, a similar approach would be to keep the larger sized generator and to use it to supply additional shelters to increase the operating load. According to ongoing Virtual Forward Operating Base (VFOB) research, baseline layouts for a 300 PAX camp (see Figure 6) supply three shelters with one 60-kW generator. Using the same allocation of 11 kW for an iECU, and 5 kW for electrical power, this amounts to 48-kW peak loading. Simulations indicate that a 60-kW generator operating at 50% load can supply the majority of heating and cooling needs of four shelters, in all climates (though some climates may require supplemental heating or cooling). By consolidating six shelters to be supplied by one generator, with iECUs required for only two of the shelters, this amounts to a peak load of 87% (52 kW) and average expected loads to be on the order of 70%. Thus, one generator can be used in place of two, and operated at higher efficiency.

Introducing the ability to store excess electricity would provide another way for the generators to be run at a higher, constant base load while maintaining the capacity to supply peak loads. This approach has been implemented in the prototype Mobile Hybrid Power System (MHPS) by Enerdel, which uses a 15-kW TQG coupled with an 80-kWh lithium ion battery mounted on a trailer. This configuration can allow the generator to operate at the optimal load of 90 to 100% of capacity, resulting in peak efficiency operation. Any excess generated energy charges the batteries until they are full, at which time the generator automatically shuts off and power is supplied from the batteries. Once the batteries are drained the generator automatically restarts and the process repeats (Johannes and Decker 2014).

3.5 Analyses

Each FOB has a particular configuration where diesel generators are distributed around the facility to provide power to various facilities. A 50 PAX baseline FOB assigns one 30-kW generator to supply electricity and environmental control to two B-Huts. A 300 PAX baseline FOB assigns one 60-kW generator to supply electricity and environmental control to three B-Huts. This analysis evaluated these typical configurations with the incorporation of WHR equipment to supply electricity and environmental control to B-Huts on FOBs. The specific calculated scenarios are:

1. Add cogeneration to the existing 30-kW generator configuration.
2. Switch from two 30-kW generators to one 60-kW generator without cogeneration.

3. Switch from two 30-kW generators to one 60-kW generator with co-generation.
4. Add cogeneration to the existing 60-kW generator configuration.
5. Reconfigure 60-kW generators for a 300 PAX FOB, thus:
   a. *Old configuration:* one 60-kW generator for three B-Huts
   b. *Proposed new configuration:* one 60-kW generator to supply electricity to six B-Huts, and cogeneration-supplied environmental control to four B-Huts.

The calculations take an average of various representative loading schedules, applied to peak loadings of the old and new configurations, taking into account changes in peak loading from applying cogeneration and consolidation of generators. Fuel usage is calculated from fuel consumption vs. percent load data for each of the generators and the results from the old and new configurations are compared.

Scenarios 1-3 represent the configuration modifications for a 50 PAX FOB, while Scenarios 4-5 represent a FOBs that are 300 PAX and greater. Table 6 lists results based on initial calculations to implement WHR in various scenarios. While these are preliminary results, the potential savings and return are significant. All scenarios show a net positive energy savings using WHR ranging from 17 to 48% fuel savings depending on the configuration. Simply switching from two 30-kW generators to one 60-kW generator in Scenario 2, at no additional cost, can provide an estimated 17.4% fuel savings due to the higher efficiency of the larger unit. The switch from two 30-kW generators to a single 60kW generator with WHR (Scenario 3) provides more potential for fuel savings at 34.2%, which would represent the typical maximum savings at a 50 PAX FOB.

Table 6. Results of implementing WHR to 30 and 60-kW generators at B-Huts on FOBs.

Scenario	Unit Fuel Savings		Equipment Cost per Unit	Annual Cost Savings	Simple Payback (yrs)
	gal/yr	%			
1	4,302	17.3%	$35,000	$65,523	0.54
2	4,287	17.4%	$0	$64,304	0.00
3	8,468	34.2%	$35,000	$127,018	0.28
4	3,989	21.9%	$35,000	$59,840	0.58
5	17,357	47.9%	$35,000	$260,354	0.13

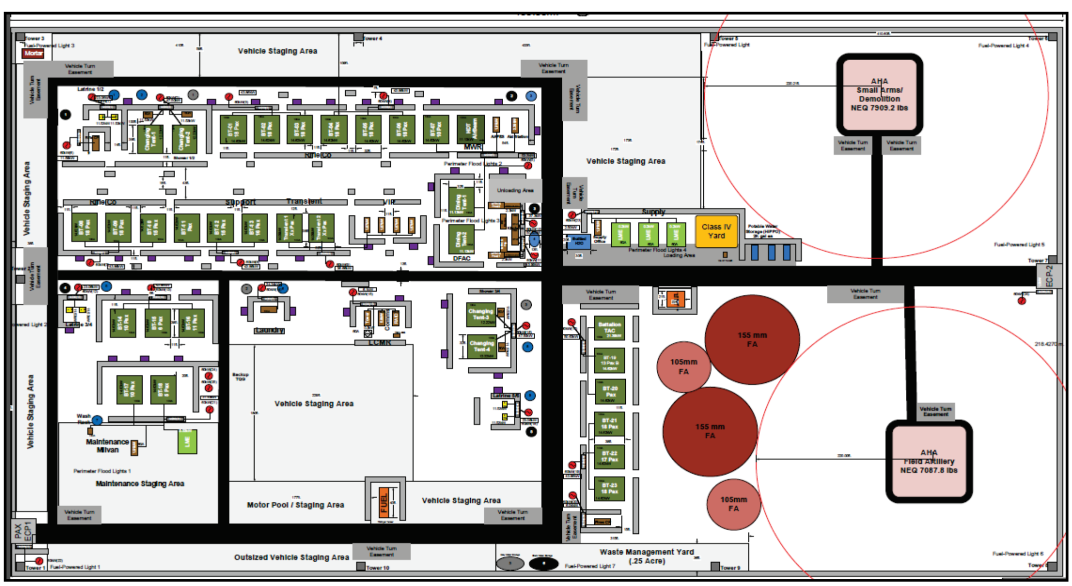
For a 300 PAX FOB, adding WHR to an existing configuration of one 60-kW generator for three B-Huts could potentially yield 21.9% fuel savings (Scenario 4). This configuration is not optimized, however, because the

WHR system could reasonably supply enough energy content for only two of the three B-Huts due to reduced loading. Scenario 5 describes a more optimized configuration in which one generator supplies electricity to six (instead of three B-Huts) and environmental control to four of the B-Huts via cogeneration. Two of the six shelters would still use ECUs. As noted in Section 3.4.3.3, the generator would operate with an average load well above 50%. This scenario yields the highest potential fuel savings at 47.9%.

3.5.1 Base camp size

Although this analysis looked only at B-Huts, it does not limit the opportunity to implement WHR for other facilities on the FOB. Each set of results in Table 6 is based on a single implementation. Thus for FOBs with more personnel, the total savings would be based on the number of configurations in which this system can be implemented. Specifically, given the number of B-Huts at a 300 PAX FOB (Figure 6) where spot generation requires 22, 60-kW generators, this configuration could be implemented up to five times. The resulting system would have the ability to satisfy the same energy demand with 17 instead of 22 generators. Assuming a baseline monthly diesel fuel consumption of 36,500 gal, this represents a 19.8% savings overall at the FOB. In logistical terms, the requirement for one 5,000-gal fuel convoy to the FOB every 4 days would be reduced to one fuel convoy every 5 days.

Figure 6. Baseline layout for 300 PAX base camp.



Source: courtesy of SLB-STO-D

In a 50 PAX camp Scenario 3 is optimal, i.e., two 30-kW generators are replaced by one 60-kW generator, with cogeneration. Based on the baseline layout, this scenario can be implemented up to two times in the 50 PAX camp, and assuming monthly fuel consumption of 7,600 gal, this represents fuel savings of up to 18.5% overall.

3.5.2 Location

For base camp locations, this analysis assumes that one 60-kW generator can supply the complete environmental control demands for four shelters. For B-Hut shelters in temperate and rain forest regions, this is a reasonable assumption. Both scenarios are predicted to cover greater than 90% of the demands for 50% loading of the generator; small levels of supplemental heating or cooling capacity may be required. In the arctic and desert climate models, greater than 82% of the demand can be covered; a significant amount of supplemental heating (arctic) or cooling (desert) would be required to meet the environmental control needs, resulting in somewhat lower overall savings. When generator loading is at 75%, in all but the arctic regions, greater than 93% of the demand can be met, while in the arctic region 88% can be met.

3.5.3 Cost

Equipment costs are assumed to be associated with additional components that can be added to existing generators. This assumption explains how there is no equipment cost for Scenario 2, in which a 60-kW generator simply replaces two 30-kW generators. The absorption chiller makes up $25,000 of the cost, and the remaining WHR components are estimated at $10,000. The costs used in Scenario 5 include all of the WHR equipment plus the use of three Tesla Powerwall units estimated at additional $25,000, and the results show better savings than the previously studied hydrogen storage and fuel cell configuration (Holcomb et al. 2007). All of the values for Cost Savings and Simple Payback are calculated assuming a burdened fuel cost of $15 per gallon of diesel fuel, which explains the significant annual savings and simple payback for each system of less than 2 years.

The initial construction of camps with WHR systems, or of retrofitting existing camps, would require the transport of additional equipment. It is estimated that, for each WHR system, the shipping volume and weight are 3 m^3 (100 cu ft) and 581 kg (1280 lb) for a system with an absorption

chiller, and 2 m^3 (70 cu ft) and 350 kg (772 lb) for a system without absorption chiller (for regions that would not require cooling).

3.6 Scope of capabilities-based assessment

3.6.1 General application

Tactical generators, which are assigned to most Army units, are often the only source of energy on the battlefield. These generators can easily be adapted to provide hot water at no additional energy cost, which will improve Soldiers' QOL in every CB environment by supplying Soldiers' with hot water for personal hygiene on the smallest scale and by providing cogeneration to heat shelters. A base camp with basic capabilities (HQDA 2013) could provide hot water heating for Solider personal hygiene and a base camp with expanded capabilities could provide heating for shelters and hot water for laundry, and showers. The ability to do this with limited additional requirements is potentially a combat multiplier on the battlefield.

3.6.2 Applicability to the current and future force (Army vision for CBs, constants, expected changes, unknowns)

According to current doctrine (HQDA 2013), "A *base camp* is an evolving military facility that supports the military operations of a deployed unit and provides the necessary support and services for sustained operations." This requirement will remain the same for now, and on the battlefield for the future force. However, what can change is how to provide support and service for sustained operations. Tactical generators are currently loaded only to 30 to 40% capacity, due in large part to the sizing of generators to cover large electrical loads like electric heating of space and water. Using the otherwise wasted thermal by-product of the diesel generator allows loads to be consolidated and generator sizes and numbers to be reduced, thereby making the Army's future force more mobile.

4 Feasibility (DOTMLPF Assessment)

This chapter reviews the implications of findings from this study. Issues or observations, discussion and recommendations from this study are grouped below by the DOTMLPF domains of Doctrine (D), Organizations (O), Training (T), Materiel (M), Leader Development and Education (L), Personnel (P), and Facilities (F).

4.1 Doctrine (D)

A primary issue in this area is that the doctrine for deployed electrical power is outdated. Field Manual (FM) 5-424, *Theater of Operations Electrical Systems*, was last published in June 1997 (HQDA 1997), but is based on content that is decades old. This FM does include the basic planning steps for identifying power requirements, selecting generators, and planning for generator operations and power distribution. These planning steps are still relevant and useful, but the overall content of this FM does not adequately address the power generation challenges of deployed units today. The Engineer School and the Maneuver Support Center of Excellence (MSCoE) began writing the ATP 3-34.45, *Deployed Electrical Power* in 2012 (HQDA 2012) to replace the outdated FM 5-424. This ATP will include a chapter on Tactical Electrical Power Systems, which is expected to include Soldier Power, Spot Generation, Low Voltage Grids, Alternative Energy, and Base Camp Power Support Models. This would be a good place to discuss WHR as well.

Another issue related s to the fact that, in July 2013, the U.S. Army Training and Doctrine Command (TRADOC)/Army Capabilities Integration Center (ARCIC) published a report *Energy to the Edge In-Theater Assessment Report,*" which discussed the role of an OE Advisor, and provided the following recommendations:

- TRADOC should take the lead for the Concept of Operations (CONOPS) revision with the MSCoE and the Engineer School as the proponent.
- Expand the OE Advisor's portfolio beyond power generation and distribution to improve energy efficiency across multiple lines of effort. (Again, WHR would be a means of achieving this.)

4.2 Organization (O)

The Army is fielding Brigade Engineer Battalions (BEBs), which are authorized a 120A Construction Engineering Technician, who could manage WHR options.

4.3 Training (T)

A critical training issue is that all leaders and Soldiers require greater OE awareness. All units need power. When units transition from maneuver operations to bases and require electrical power beyond the capabilities of their organic generators and vehicles, they require more knowledge and planning skills. While leaders in units are increasingly aware of generator operations and maintenance issues, such as wet stacking under low loads, they are not trained on power management, generator operations and maintenance, and power distribution in TRADOC schools. WHR could be added as this training is developed.

A second training issue is that Generator Mechanics (Military Occupational Specialty [MOS]) 91Ds are not located on all outposts. Consequently, other mechanics end up performing most of the generator maintenance on outposts. A direct solution would include:

- Ensure that 120As assigned to the BEB in a Brigade Combat Team (BCT) receive training in WHR options to enable them to assist in management.
- All incidental operators of any Army WHR system should meet minimum training requirements before being allowed to operate a WHR system.

4.4 Materiel (M)

WHR systems should be developed to work with program of record equipment. WHR can then be introduced with that equipment training.

4.5 Leader development and education (L)

Leaders are not trained to address the power challenges on base camp or to plan for power generation and distribution. Leaders are not currently trained in TRADOC schools, in units, or in pre-deployment training on how to deal with all the power challenges they will face on outposts. As a result, leaders on outposts and within BCTs are not trained to recognize or

judge optimal performance of outpost power generation and distribution. They cannot accurately assess power generation and distribution problems or develop solutions to their power issues without the OE Advisors. These leaders are heavily reliant on contractor support.

All incidental operators of any Army WHR system and their leaders should meet minimum training requirements before being allowed to operate a WHR system.

4.6 Personnel (P)

All incidental operators of any Army WHR system should meet minimum training requirements before being allowed to operate a WHR system.

4.7 Facilities (F)

Only limited changes to outpost facilities would be required to incorporate WHR options.

5 Conclusions and Recommendations

5.1 Conclusions

Tactical generators are currently loaded only to 30 to 40% capacity, due in large part to the sizing of generators to cover large electrical loads like electric heating of space and water. It is concluded from the data and calculations summarized in this report that using the otherwise wasted thermal by-product of the diesel generator allows loads to be consolidated so the numbers and sizes of generators can be dramatically reduced:

- Water heating can be supplied for an entire 300 PAX with five 60-kW generators' waste heat (Section 3.5, p 29).
- For 15 out of 16 generator size/location combinations, cogeneration can be implemented on at least one B-hut structure (Tables 2 and 5, p 10).
- Implementation of cogeneration can lead to total fuel savings of 19.8% over baseline configuration in a 300 PAX base camp and fuel savings of up to 18.5% in a 50 PAX base camp (Section 3.5.1, p 31). This reduces the need for fuel convoys from one every 4 days to one every 5 days.
- Instantaneous water heating can be supplied in austere conditions from low flow up to shower rates (1.75 gpm) per implementation. This has potential to significantly increase the QOL for camps with basic services.

5.2 Recommendations

Additional research is recommended to further refine the results of this work. Additional research would be used to identify applications where the use of generator WHR will allow OE to be used most effectively. In general, the use of WHR for cogeneration is recommended as this will reduce energy demands and allow consolidation of generators. The use of WHR for water heating, which will also reduce energy demands and increase QOL, is also recommended.

Acronyms, Abbreviations, and Technical Terms

Acronyms and Abbreviations

Term	Definition
AMMPS	Advanced Medium Mobile Power Sources
ARCIC	Army Capabilities Integration Center
ARE	Arab Emirate
ASME	American Society of Mechanical Engineers
ATP	Army Doctrine and Training Publication
ATTP	Army Tactics, Techniques, and Procedures
AWG	Atmospheric Water Generator
BCT	Brigade Combat Team
BEB	Brigade Engineer Battalion
BGR	Bulgaria (ISO Country Code)
BLZ	Belize (ISO Country Code)
BRA	Brazil (ISO Country Code)
CB	Contingency Base
CCHP	Combined Cooling, Heat and Power
CCP	Concept Capability Plan
CEERD	U.S. Army Corps of Engineers, Engineer Research and Development Center
CERL	Construction Engineering Research Laboratory
CHN	China (ISO Country Code)
CHP	Combined Heat and Power
CMU	Concrete Masonry Unit
CONOPS	Concept of Operations
COTS	Commercial off-the-Shelf
DFAC	Dining facility
DMMS	Deployable Metering and Monitoring System
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities
DTIC	Defense Technical Information Center
E2E	(Rapid Equipping Force's) Energy to the Edge
ECU	Environmental Control Unit
EGY	Egypt (ISO Country Code)
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
ESP	Spain (ISO Country Code)

Term	Definition
ExFOB	[Marines] Experimental Forward Operating Base
FIN	Finland (ISO Country Code)
FM	Field Manual
FOB	Forward Operating Base
GTM	Guatemala (ISO Country Code)
HND	Honduras (ISO Country Code)
HRI	Heat Recovery Incineration
ISL	Iceland (ISO Country Code)
ITA	Italy (ISO Country Code)
JP-8	Jet Propellant 8 (a kerosene-based fuel)
KEN	Kenya (ISO Country Code)
LKA	Sri Lanka (ISO Country code)
MCRP	Marine Corps Reference Publication
MEP	Mobile Electric Power
MHPS	Marine Corps Reference Publication
MOS	Military Occupational Specialty
MSCoE	Maneuver Support Center of Excellence
MW	Megawatt
NOR	Norway (ISO Country Code)
NREL	National Renewable Energy Laboratory
OE	Operational Energy
ORC	Organic Rankine Cycle
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PAX	Personnel
PCM	Phase Change Material
PEMFC	Proton-Exchange Membrane Fuel Cell
PEX	Cross-Linked Polyethylene
PNNL	Pacific Northwest National Laboratory
PRK	People's Republic of Korea (ISO Country Code)
QOL	Quality of Life
RUS	Russia (ISO Country Code)
SAU	Saudi Arabia (ISO Country Code)
SLB-STO-D	Sustainability Logistics Basing-Science and Technology Objective-Demonstration
SOFC	Solid Oxide Fuel Cell
TEEPS	Thermal Energy to Electric Power System
TES	Thermal Energy Storage
TNT	Trinitrotoluene
TOC	Tactical Operations Center
TQG	Tactical Quiet Generator

Term	Definition
TR	Technical Report
TRADOC	U.S. Army Training and Doctrine Command
UIUC	University of Illinois at Urbana-Champaign
URL	Universal Resource Locator
UV	Ultraviolet
VFOB	Virtual Forward Operating Base
VW	Volkswagen
WHR	Waste Heat Recovery
WtE	Waste-to-Energy
WWW	World Wide Web

Technical terms

Arctic Climate

This climate typically experiences year-round cold temperatures, reduced heat from sunlight, strong winds and varying precipitation, but very low humidity. Temperature extremes throughout the year run from -50 °C to 10 °C (-58 to 50 °F). Example cities include: Helsinki FIN, Reykjavik ISL, Oslo NOR, St. Petersburg RUS, and Yakutsk RUS. Note, although the Arctic and Antarctic regions are climatologically considered deserts, for the purposes of this study, this term focuses more on the effect of temperature extremes rather than the humidity.

Combined Heating and Power (CHP)/Cogeneration

The use of the remaining thermal energy from any electrical generator based on a temperature differential (typically combustion, but could be other) that is normally lost to the environment, and is harnessed for the purposes of heating buildings and structures directly, without conversion to electricity. This is also known as cogeneration. The same concept can be used to also produce cooling power from the waste heat in a combined cooling, heating and power (CCHP or trigeneration) system.

Desert Climate

This climate typically experiences year-round hot temperatures, increased heat from sunlight, strong winds and minimal precipitation, and very low humidity. Temperature extremes throughout the year run from -5 to 60 °C (23 to 140 °F). Example cities include: Abu Dhabi ARE, Kharga EGY, Riyahd SAU, and Phoenix, AZ.

Point-of-Use

Heated water that is used directly and consequently removed from the system (showers, shave stands, coffee, kitchens, etc.), and therefore not used for environmental purposes.

Practical Energy

The fraction of waste heat energy that can reasonably be expected to be extracted from the overall system, taking into account efficiencies of heat exchangers, line loss transport, etc.

Rain Forest Climate

This climate typically experiences year-round hot temperatures with very high humidity. Temperature extremes throughout the year run from 15 to 35 °C (59 to 95 °F). Heat due to sunlight is moderate depending on vegetation level. Wind is generally low, precipitation levels are usually high, but vary in frequency and intensity over the course of the year. Example cities include: Belize BLZ, Salvador BRA, Puerto GTM, La Ceiba-Goloson HND, Kisumu KEN, Colombo-Ratmalana LKA, and Hilo, HI.

Temperate Climate

This climate typically experiences a four season cycle, with a warm summer, cold winter, and varying winds and precipitation throughout the year. Temperature extremes throughout the year run from -40 to 40 °C (40 to 104 °F). Heat due to sunlight is moderate depending on vegetation level. Example cities include: Beijing CHN, Pyongyang PRK, Plovdiv BGR, Burgos ESP, Champaign (Willard Airport), IL, and Rolla (Airport), MO.

Waste Heat

Thermal energy generated as a result of exothermic reactions, typically combustion, which is contained in the exhaust of engines. This energy is typically lost to the environment through the exhaust stream and by conduction through the combustion chamber to the engine block. This study focuses on the exhaust stream; the term "Waste Heat" henceforth will refer to only the waste heat from the exhaust stream. This excess energy is equal to the mass of the exhaust (kg), multiplied by the heat capacity, Cp (J/kg-°C), and multiplied by the difference in exhaust temperature (° C) and ambient temperature.

Working Fluid

The medium used to transfer the recaptured waste heat from where it is generated to where it is stored and ultimately used. This can be a single liquid (e.g., water), or a mixture of liquids (e.g., water and ethylene glycol).

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Appendix A: Heating and Cooling Demands That Can Be Met through Waste Heat Recovery

Table A-1. The percent of heating and cooling demands for 2 B-Huts that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions.

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	62.29%	10.93%	64.64%	6.82%	60.12%	8.69%	73.43%	4.11%
15kW AMMPS	72.35%	12.19%	75.80%	5.75%	78.05%	7.89%	84.31%	3.67%
30kW AMMPS	87.85%	13.46%	93.11%	2.84%	97.49%	1.24%	96.66%	2.43%
60kW AMMPS	95.49%	9.37%	99.89%	0.13%	99.99%	0.01%	99.74%	0.42%
10kW TQG	67.85%	11.64%	70.78%	6.29%	70.03%	8.74%	79.59%	3.90%
30kW TQG	90.72%	13.01%	96.38%	1.87%	99.09%	0.60%	98.16%	1.77%
60kW TQG	93.22%	11.83%	98.79%	0.82%	99.84%	0.14%	99.16%	0.99%

Table A-2. The percent of heating and cooling demands for 2 AirBeam tents that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions.

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	71.76%	9.16%	69.59%	5.28%	61.61%	5.79%	76.78%	2.33%
15kW AMMPS	83.67%	8.70%	81.92%	4.26%	78.82%	3.82%	88.19%	1.79%
30kW AMMPS	96.79%	4.89%	97.44%	1.34%	98.56%	0.82%	99.40%	0.32%
60kW AMMPS	99.99%	0.02%	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%
10kW TQG	78.65%	9.07%	76.47%	4.81%	71.29%	4.84%	83.37%	2.08%
30kW TQG	98.40%	3.27%	99.35%	0.61%	99.88%	0.10%	99.96%	0.04%
60kW TQG	99.44%	1.22%	99.97%	0.03%	99.99%	0.00%	99.99%	0.01%

Table A-3. The percent of heating and cooling demands for three B-Huts that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions.

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	53.30%	9.64%	52.73%	7.52%	42.52%	7.55%	62.12%	4.42%
15kW AMMPS	62.60%	10.90%	63.09%	6.96%	57.96%	8.76%	73.09%	4.19%
30kW AMMPS	79.25%	12.90%	82.17%	4.94%	87.10%	5.52%	90.33%	3.38%
60kW AMMPS	92.48%	12.23%	97.87%	1.27%	99.62%	0.32%	98.87%	1.24%
10kW TQG	58.35%	10.33%	58.33%	7.26%	50.62%	8.27%	68.13%	4.31%
30kW TQG	83.60%	13.28%	87.22%	4.11%	92.82%	3.27%	93.75%	3.05%
60kW TQG	88.18%	13.33%	92.66%	2.94%	97.31%	1.33%	96.76%	2.38%

Table A-4. The percent of heating and cooling demands for three AirBeam tents that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	59.93%	8.37%	56.57%	5.69%	44.23%	6.37%	64.62%	2.48%
15kW AMMPS	72.37%	8.82%	67.82%	5.43%	59.46%	6.10%	76.47%	2.24%
30kW AMMPS	90.35%	7.25%	88.35%	3.28%	87.35%	2.68%	93.94%	1.18%
60kW AMMPS	99.19%	1.76%	99.85%	0.19%	99.99%	0.01%	99.99%	0.01%
10kW TQG	66.78%	8.71%	62.55%	5.62%	52.22%	6.38%	71.13%	2.39%
30kW TQG	93.86%	6.12%	92.87%	2.36%	93.12%	1.99%	97.07%	0.78%
60kW TQG	97.07%	4.47%	97.14%	1.42%	98.35%	0.92%	99.41%	0.31%

Table A-5. The percent of heating and cooling demands for four B-Huts that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions.

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	47.48%	8.83%	45.36%	7.72%	32.85%	6.56%	54.79%	4.58%
15kW AMMPS	56.02%	9.98%	54.69%	7.47%	45.36%	7.93%	64.94%	4.43%
30kW AMMPS	72.24%	12.03%	73.27%	6.03%	74.59%	8.55%	83.47%	3.78%
60kW AMMPS	88.75%	13.24%	93.06%	2.83%	97.58%	1.22%	97.05%	2.27%
10kW TQG	52.09%	9.44%	50.34%	7.64%	39.30%	7.32%	60.25%	4.51%
30kW TQG	76.84%	12.56%	78.68%	5.41%	82.65%	6.96%	88.03%	3.52%
60kW TQG	82.38%	13.13%	85.14%	4.47%	90.71%	4.17%	92.71%	3.17%

Table A-6. The percent of heating and cooling demands for four AirBeam tents that can be met through WHR from various generators operated at 50% loading for 1 year, averaged over several locations in each of four climate regions.

	Arctic	std. dev.	Desert	std. dev.	Rain Forest	std. dev.	Temperate	std. dev.
10kW AMMPS	52.36%	7.71%	48.89%	5.63%	34.54%	6.08%	56.78%	2.48%
15kW AMMPS	63.78%	8.41%	58.60%	5.73%	47.03%	6.51%	67.77%	2.41%
30kW AMMPS	83.68%	8.20%	79.19%	4.57%	75.59%	4.45%	87.26%	1.76%
60kW AMMPS	97.45%	4.11%	97.42%	1.34%	98.66%	0.80%	99.56%	0.25%
10kW TQG	58.48%	8.11%	54.03%	5.74%	41.02%	6.39%	62.71%	2.46%
30kW TQG	88.22%	7.56%	84.93%	3.87%	83.16%	3.32%	91.72%	1.39%
60kW TQG	92.95%	6.31%	91.07%	2.73%	90.92%	2.30%	96.09%	0.90%

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14. ABSTRACT
The energy requirements of contingency bases (CBs) involved in U.S. military operations on every continent are met almost exclusively with the use of diesel generators, which are relatively inefficient both in terms of fuel consumption and the large amounts of waste energy generated during their operation. Tactical generators are currently loaded only to 30 to 40% capacity, due in large part to the sizing of generators to cover large electrical loads like electric heating of space and water. This work was undertaken to estimate the amount of available waste heat that could be captured and reused to heat (or cool) buildings and provide hot water while reducing generator fuel demand. It was found that the use of otherwise wasted thermal by-product of the diesel generator for space and water heating allows loads to be consolidated so the numbers and sizes of generators can be dramatically reduced. The use of cogeneration can lead to total fuel savings of nearly 20%. Waste heat from five 60 kW generators can supply water heating for an entire 300 PAX contingency base, and in austere conditions, one 30 kW generator can provide up to 1.75 gpm of instantaneous hot water.

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